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SOME SIMPLE USES OF INSTRUMENTAL DATA

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A. Measuring the Strength of Ground Motion

In general terms, the characteristics of strong ground motion are amplitude, duration and frequency content. Unfortunately, applying these terms to a record of ground acceleration and determining numerical values is not a straightforward process because of the complexity of the motion. The forces on a structure are proportional to the mass of a structure times the acceleration of the ground, indicating that the fundamental parameter of motion for engineering is the ground acceleration, rather than the simpler motions of velocity or displacement. The problem of measuring the strength of ground motion therefore becomes the application of the concepts of duration, amplitude and frequency content to records such as shown in Figure 1, which is taken from the EERI Monograph, Earthquake Design Criteria.

The easiest way to measure the amplitude of motion is simply to use the peak value of the acceleration. This is a common practice and peak acceleration is used widely as a rule-of-thumb measure of the strength of shaking. However, a study of the accelerations in Figure 1 suggests rather strongly that this approach will have serious limitations if it is used as a sole measure of the shaking; the records in Figure 1 all have the same peak acceleration, but their effects on structures will cover a wide range of responses. In some cases the peak acceleration is more representative than in others. Compare, for example, the records from Olympia, S86W and Hachinohe Harbor EW that are given in Figure 1.

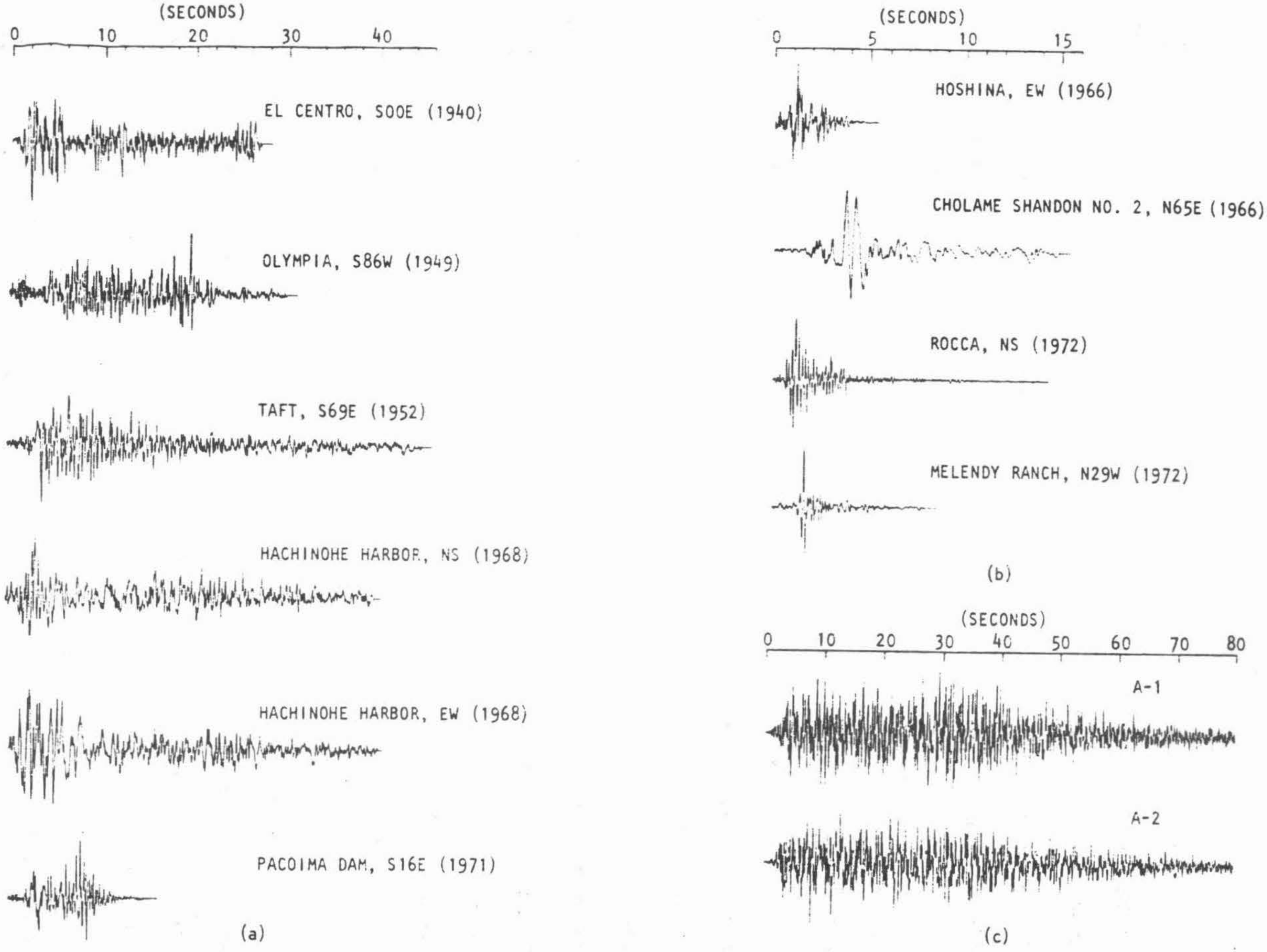

Figure 1. Accelerograms from different earthquakes. Group (a) shows accelerograms from $M_S = 6\frac{1}{2}$ to $7\frac{1}{2}$ earthquakes. Group (b) includes records obtained close to the fault in smaller earthquakes, plotted to a different time scale. The much longer records in group (c) are artificially generated accelerograms modeling the expected ground motion close to the fault in a great (M_S = 8+) earthquake.

The occurrence of an isolated, unrepresentative peak in the motion, such as occurs in the Olympia record, is one of the reasons for the introduction of the concept of "effective peak acceleration" or "sustained peak acceleration." There are various definitions for these reduced measures of acceleration, but they all have the common feature of attempting to determine a value of acceleration, more representative than the peak value, that can be used directly in the formulation of criteria for earthquake resistant design. In the writer's view, the advantages gained by this approach are rather small. The characterization of strong ground motion for design by a single parameter is, I believe, a serious oversimplification of the complex problem of earthquake response. It seems necessary that some measures of frequency content and duration must also be considered.

Accelerograms like those shown in Figure 1 produce chaotic forces that excite structures with a wide range of natural frequencies. Earthquake motions are audible close to the source in some cases, indicating frequencies as high as 20-50 Hz. On the other end of the scale, seismologists measure wave motions with hundreds of seconds period during great earthquakes. In this context, the question of how strong the shaking is for a particular structure can be addressed by performing a spectral analysis which measures the strength of motion as a function of frequency. The two most commonly used methods of spectral analysis are the Fourier spectrum and the response spectrum, both of which are addressed later in this Seminar. For purposes of earthquake-resistant design, the response spectrum is the more directly useful method. For each mode of response of a structure, the response spectrum ordinate at that frequency can be used to find the maximum response of that mode to the accelerogram under consideration. For simple structures with only one significant degree of freedom, the response spectrum ordinate for the period and damping of the structure directly specifies the maximum earthquake response. Because of these applications, the response spectrum is a useful way to measure the frequency content of the motion. It should be pointed out, too, that the period dependence of seismic forces given in building codes reflects the frequency content of strong ground motion.

For purposes of research, the Fourier spectrum is usually preferable to the response spectrum, however; it has mathematical advantages in analysis that are not possessed by the response spectrum.

Although both the response spectrum and the Fourier spectrum are affected by the duration of motion, the relation is indirect and it is often desirable to have a direct measure of the duration of strong shaking. The duration of shaking is particularly important for the nonlinear response that is expected in many structures during very strong excitation. For nonlinear, yielding response, the most important question is how close the structure is to failure and the duration of strong shaking has been found to be an important parameter in trying to answer this question. It is obvious, for example, that the Melendy ranch and the El Centro, 1940 records in Figure 1 will cause widely different responses in nonlinear, yielding structures.

Several measures of duration have been proposed, but there is not a clear consensus on which definition is preferable. For some purposes, a rule-of-thumb measure is adequate. For example, noting by inspection that the strong shaking at Pacoima Dam in 1971 was about 10 seconds long, whereas the artificial earthquakes A-1 and A-2 have about 50 seconds of strong shaking, often is enough. This approach can be systemitized by defining the duration as the time between the first and last acceleration peaks of a specified amplitude (e.g., 5 percent g). Other measures of duration have been derived from examination of plots of the square of the ground motion as a function of time. One measure of this type is the time it takes for the accelerogram to deliver the central 80 percent of its energy.

B. Estimating the Periods of Vibration of Structures

The acceleration records obtained in buildings are a sum of the acceleration of the ground and the acceleration of the instrument with respect to the ground. Because of this, records obtained in buildings contain a mixture of information about ground shaking and structural response. This can be seen in Figure 2, which shows the acceleration records obtained in Building 180 at the Jet Propulsion Laboratory in Pasadena during the February 9, 1971 San Fernando earthquake. The displacements of the roof and the ground, calculated from the acceleration records by integrating twice, are also given in the figure. Immediately after the earthquake, only acceleration records will be available in most cases, because digitization and data processing are required before the displacements can be calculated.

Visual examination of the records is often sufficiently accurate to identify natural periods of vibration of the structure. Comparison of the displacement records shows that the motion of the roof consists of the vibratory motions of the building in its first mode, superimposed upon the longer-period motions of the ground. In the case of the accelerations, the first part of the roof motion consists of a strong

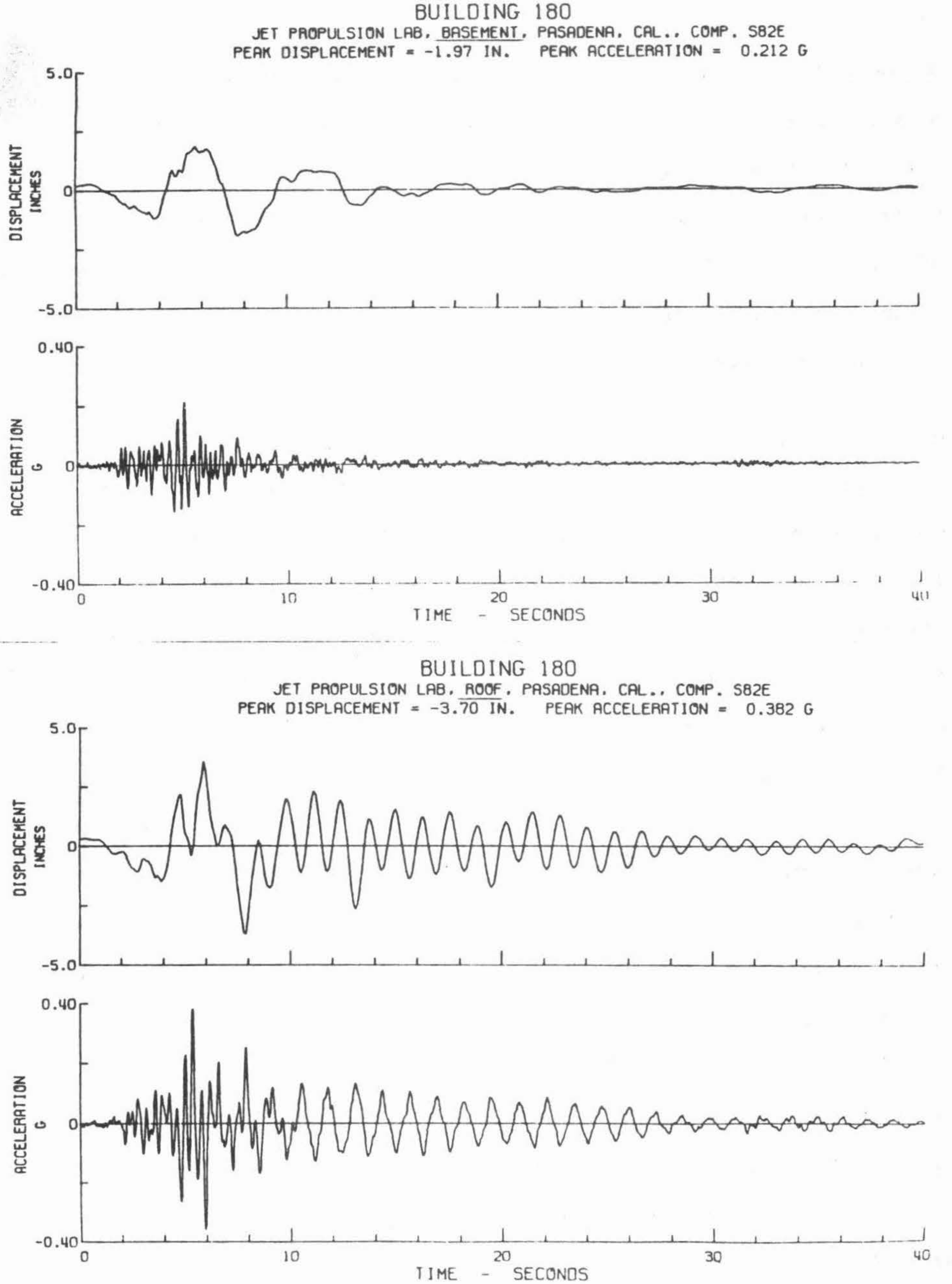

Fig. 2. Basement and roof motions recorded in Building 180, Jet Propulsion Laboratory, Pasadena during the San Fernando earthquake of February 9, 1971. The motion at the roof is the total motion, that of the building plus that of the ground. This is most clearly seen in the displacement of the roof, wherein the oscillations of the building are superimposed on the longer-period motions of the ground.

mixture of ground and building motions, but the later part of the roof acceleration record is dominated by the response of the structure in its fundamental EW mode. The natural period of this motion is found by noting the time for a given number of cycles to be about 1.3 seconds. The roof motion between four and six seconds has the appearance of a higher mode of response. However, motion of this period also appears in the basement record at this time, so it may be wrong to attribute this to structural response in a single mode. The higher frequency motions between eight and ten seconds are more likely attributable to structural response and suggest the response of a mode with a period of about 0.45 sec. Because this period is about one-third of that of the fundamental mode, it probably is the second mode of response. Fortunately, the period of the fundamental mode is the most important period, and it is the easiest to identify.

In many instances, records will be available from three points on the building, typically the roof, basement and mid-height. With the additional records from mid-height, it is possible to determine higher mode periods with more confidence, as well as to estimate mode shapes and other important characteristics of response. Detailed examples of how this may be done are given in Appendix A of the EERI monograph Earthquake Design Criteria.

C. Calculating Base Shear and Other Force Resultants

When a relatively simple structure, such as a tall building with a uniform, rectangular cross-section, vibrates back-and-forth in its fundamental mode, the shear force at the base of the building oscillates with the motion. The maximum value of base shear occurs when the building reaches its maximum deflection -- this is when the restoring forces are greatest. Similarly, the shear force is zero when the building passes through its equilibrium position. The base shear during an earthquake includes contributions from several modes of vibration, but the base shear from the fundamental mode is usually larger than that from other modes and it usually persists longer in time. This can be seen in the roof motions given in Figure 2; strong fundamental mode response lasts almost 20 seconds. The shear in the structure at its base is often of particular interest, for example, for comparison with the base shear prescribed in the building code, but the shear at other levels is also important and can be found by the same type of analysis used to estimate base shear.

If records of the building response are available, the shears (and moments) in the building during the earthquake can be estimated directly from the recorded accelerations by simple hand calculations. The additional information required is the mass distribution of the building and the mode shapes of those periods identified in the response. The mode shape can usually be estimated from the earthquake response, as well, so the mass distribution of the structures is all that is required. In particular, the stiffness matrix is not needed. To estimate the shears and moments throughout the structure when vibrating in a particular mode, the structure is visualized to be at its maximum point of free vibrations in that mode, with the inertia forces treated as static forces. The amplitude of the forces at the various levels of the structure is determined by the maximum measured acceleration in that mode during the earthquake and by the estimated mode shape. This part of the analysis gives the acceleration profile for the structure. The acceleration at each point, expressed as a fraction of g, is then multiplied by the mass, expressed as the weight divided by g. The gravitational constant drops out of the calculation, leaving the inertia force in the correct units. The resulting forces are treated just like static forces to find the base shear, base moment and shears and moments elsewhere in the structure.

Using the same acceleration profile, the displacements of the structure with respect to the base can be found by another simple calculation. Using the fact that for harmonic motion, the displacement is $T^2/4\pi^2$ times the acceleration, where T is the period of the mode, the displacement profile is readily determined. The displacements are interesting in their own right, and also allow the calculation of interstory drift which is important for the response of partitions and other nonstructural features of the building.

The procedure for making these calculations is explained in detail in Appendix A of Earthquake Design Criteria, which also includes an example from the San Fernando earthquake.